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Review

Scouring Mechanism of Roadbeds at Curved Sections of River-Adjacent Highways

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Abstract: Highways constructed along river bends face heightened vulnerability to scour due to complex hydrodynamic behaviors, intensified outer-bank erosion, and highly erodible riverbank soils. This review synthesizes current knowledge on the flow structures at curved river sections, the mechanisms governing roadbed–river interactions, and the typical failure modes triggered by progressive scour. It further examines the key influencing factors—hydraulic, geometrical, geotechnical, and anthropogenic—that collectively determine scour severity. Existing engineering protection techniques, modern monitoring tools, and advanced numerical and physical modeling methods are evaluated to highlight their applicability and limitations. The review concludes by identifying emerging research priorities, including AI-based scour forecasting, fully coupled hydro–geotechnical–structural modeling, climate-resilient design strategies, and ecological protection approaches. Overall, this study provides an integrated understanding of scour processes affecting river-adjacent highway roadbeds and offers guidance for more resilient and sustainable infrastructure development.

Keywords: riverbend scour; highway roadbed stability; hydrodynamic–geotechnical interaction; monitoring and modeling; climate-resilient infrastructure

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1. Introduction

Highway development along river valleys has expanded rapidly over the past several decades as governments seek to improve regional connectivity, support economic growth, and enhance access to remote mountainous areas. In many countries, the most feasible transportation corridors naturally follow riverbanks, where terrain is relatively gentle compared with surrounding high-relief landscapes. While these river-adjacent highways offer significant socioeconomic benefits, their exposure to dynamic fluvial environments has simultaneously introduced a range of geotechnical and hydraulic challenges [1]. Among these challenges, riverbank erosion and the associated scouring of highway roadbeds have become major threats to infrastructure reliability and long-term serviceability. Repeated flood events, climate-driven hydrological variability, and increasingly complex river–land interactions have resulted in a growing number of roadbed failures, embankment collapses, and pavement deformations in river-adjacent highway sections worldwide. These incidents have highlighted the urgent need for systematic understanding and mitigation of scour processes that operate at the interface between hydraulic forces and geotechnical stability [2].

Within river-adjacent highways, curved sections represent particularly high-risk zones due to their unique hydrodynamic characteristics. Unlike straight river reaches, curved channels induce complex and asymmetric flow fields that significantly magnify local scour potential. Flow acceleration along the outer bank generates elevated velocities, steep velocity gradients, and intensified bed shear stresses. Simultaneously, the development of secondary flow—manifested as helical or spiral circulation—redistributes momentum toward the outer bank and downwards toward the riverbed. This combined action produces highly non-uniform hydraulic environments that differ fundamentally from those in straight channels. As a result, the outer-bank toe of a highway embankment may experience concentrated erosion, undercutting, and progressive retreat, ultimately compromising the structural stability of the roadbed. Sediment detachment, bank scouring, soil softening, and slope destabilization often evolve concurrently, forming an erosion–deformation coupling process that can lead to catastrophic failures during extreme hydrological events. In addition, curved sections tend to amplify localized turbulence structures, such as vortex shedding and turbulent bursts, which further accelerate sediment entrainment and exacerbate erosion hazards. These distinctive hydraulic and sediment transport behaviors make curved river sections particularly vulnerable, demanding targeted investigation to develop effective assessment and mitigation frameworks [3].

Despite the increasing recognition of scour hazards along river-adjacent highways, existing research has primarily focused on bridge scour—especially around piers, abutments, and other structural elements [4]. Bridge scour studies are supported by extensive experimental data, well-established predictive models, and standardized design guidelines. However, the mechanisms of roadbed scour adjacent to riverbanks differ substantially from bridge scour in several critical aspects. First, roadbeds present long, continuous interfaces rather than isolated structural members, resulting in broader spatial impact zones and more complex erosion patterns. Second, the interaction between flowing water and natural or engineered slopes introduces additional processes such as toe erosion, bank mass wasting, piping, and soil–water interaction effects that are not adequately represented in bridge scour models. Third, the alignment of highway embankments relative to the river channel—whether parallel, oblique, or curved—exerts a strong influence on the distribution of hydraulic forces, sediment transport pathways, and failure modes [5]. As a consequence, applying bridge scour methodologies directly to the assessment of roadbed scour can lead to significant underestimation of risk and insufficient engineering protection. Furthermore, compared with the extensive literature on bridge scour, systematic reviews specifically addressing scour mechanisms of roadbeds in curved river-adjacent sections remain notably scarce. Current knowledge is fragmented across hydraulic engineering, geotechnical engineering, fluvial geomorphology, and transportation infrastructure research, underscoring the need for integrated synthesis [6].

Given these gaps, the objective of this review is to comprehensively examine the scouring mechanisms affecting highway roadbeds located along curved sections of river channels. The review aims to integrate hydrodynamic theory, geotechnical behavior, and river morphodynamics to provide a multi-disciplinary understanding of how flow patterns, sediment transport processes, soil properties, and roadbed structures interact to produce localized or widespread scour hazards [7]. Particular emphasis is placed on identifying how the unique features of river bends—specifically secondary flow, shear stress amplification, and turbulence intensification—contribute to different roadbed failure modes. In addition, the review summarizes key influencing factors, including hydraulic forces, soil erodibility, channel geometry, anthropogenic disturbances, and environmental changes such as climate-driven hydrological extremes. By consolidating the existing theoretical, experimental, numerical, and field-monitoring findings, this work seeks to provide engineers and researchers with a clear and coherent framework for understanding scour in these high-risk environments [8].

2. Hydrodynamic Characteristics at River Bends

River bends exhibit highly complex and spatially heterogeneous flow patterns that differ fundamentally from those in straight channels. These unique hydrodynamic characteristics play a decisive role in determining the magnitude, distribution, and evolution of scour processes affecting highway roadbeds situated along curved riverbanks. Understanding the mechanisms that govern flow structure, sediment transport, and localized energy concentration is therefore essential for accurately evaluating scour potential in river-adjacent highway sections. In particular, three hydrodynamic features—primary flow redistribution, secondary circulation, and turbulence intensification—serve as the primary drivers of outer-bank erosion and roadbed instability. A structured overview of these hydrodynamic actions and their implications is provided in Table 1, which summarizes the major flow mechanisms influencing scour development at curved river sections.

Table 1. Major Hydrodynamic Actions Influencing Roadbed Scour at Curved River Sections.

Hydrodynamic Action	Source	Effect on Scour	Typical Location
Flow acceleration	Centrifugal forces pushing velocity core outward	Increases shear stress; enhances sediment entrainment	Outer bank toe
Flow deceleration	Reduced velocity near inner bank	Promotes deposition; reduces scour	Inner bank
Secondary (helical) flow	Interaction of centrifugal force, bed friction, and vertical velocity gradients	Drives near-bed flow toward outer bank; intensifies toe erosion	Outer-bank sub-bed region
Turbulent bursts	Rapid velocity fluctuations	Produces transient peak shear stresses; accelerates sediment detachment	Outer-bank bed surface
Vortex shedding	Flow interaction with bank irregularities	Repeated sediment disturbance and removal	Near bankline irregularities
Horseshoe vortices	Downward-impinging high-velocity flow	Deepens local scour holes; destabilizes roadbed toe	At bank toe or protection structures

2.1. Primary and Secondary Flow Mechanisms

At curved river sections, the primary flow undergoes significant redistribution due to centrifugal forces generated as water negotiates the bend. As the flow moves downstream, centrifugal acceleration pushes the higher-velocity core toward the outer bank. This displacement causes velocity amplification along the outer bank and corresponding deceleration along the inner bank, producing a pronounced cross-sectional velocity asymmetry. The resulting flow acceleration increases the hydraulic energy and shear stresses acting on the outer-bank toe, directly enhancing the potential for sediment entrainment and bank erosion. Conversely, the inner-bank zone typically experiences flow deceleration, lower shear stresses, and sediment deposition, contributing to the formation of point bars and asymmetric river cross-sections.

Superimposed on this primary flow redistribution is the development of secondary flow, often described as helical or spiral circulation. Secondary flow arises when the lateral pressure gradient induced by centrifugal force interacts with bed friction and vertical velocity gradients. As a result, water near the surface flows outward toward the outer bank, while near-bed flow moves inward toward the inner bank. This three-dimensional motion generates a rotational flow pattern that continually transports momentum, sediments, and fine particles across the channel. For river-adjacent highway roadbeds, secondary flow is particularly critical because it drives near-bed velocities toward the outer bank, intensifying toe scouring and accelerating the onset of undercutting. The combined influence of outward surface flow and inward near-bed return flow also tends to steepen the outer-bank bed slope, creating an erosive environment that becomes especially hazardous during flood events [9].

The interplay of primary and secondary flow not only modifies velocity distributions but also governs the spatial concentration of bed shear stresses. Depth-averaged shear stresses increase sharply along the outer bank, while the inner bank remains comparatively protected. In curved sections with small radius ratios or abrupt planform transitions, shear stress amplification can be extreme, producing localized scour holes and destabilizing the adjacent road embankment. These flow-driven asymmetries form the hydrodynamic foundation upon which more complex turbulence structures develop [10].

2.2. Turbulence Structures and Local Scour Drivers

Turbulence plays a critical role in regulating sediment entrainment, local scour depth, and transient erosion events along curved riverbanks. The interaction between primary flow acceleration, secondary circulation, and the irregular geometry of natural channels generates highly energetic turbulence structures that significantly augment scouring processes near highway roadbeds.

One of the most influential mechanisms is the occurrence of turbulent bursts—short-lived but intense fluctuations in velocity that generate localized peaks in bed shear stress. These bursts accelerate sediment detachment and transport, particularly along the outer bank where hydraulic energy is concentrated. Similarly, vortex shedding, produced as flow interacts with irregularities in the bed or bankline, creates oscillatory pressure fields capable of repeatedly destabilizing near-bank sediments. These vortices often attack the toe region of highway embankments, undermining slope stability and inducing progressive erosion [11].

Another critical turbulent feature is the development of horseshoe vortices near the outer bank, particularly in zones where the roadbed toe or protective structures interrupt the flow. These vortices form as high-velocity flow impinges on the bankline and is forced downward, producing a recirculating flow that sweeps sediment away from the toe. Such vortical systems intensify scour depth and accelerate the exposure of unprotected subgrade material. During high-flow or flood conditions, the frequency and intensity of these vortices increase, leading to sudden, transient scour events capable of causing rapid structural deterioration [12].

Collectively, these turbulence-driven processes make curved river sections hotspots for localized scour, especially where roadbeds lie close to the eroding outer bank. Their impacts often exceed those predicted by depth-averaged hydraulic models, underscoring the need for detailed three-dimensional understanding of flow structures when assessing scour risk [13].

3. Roadbed–River Interaction and Scour Mechanisms

Highway roadbeds located adjacent to river channels interact continuously with the fluvial environment, and this interaction governs the initiation and progression of scour-related damage. At curved river sections, the combination of asymmetric flow patterns, concentrated hydraulic forces, and geotechnical vulnerabilities creates a dynamic erosion–deformation system that poses a severe threat to the long-term performance of embankments and roadway structures. This chapter examines the types of roadbeds commonly encountered along rivers, outlines the fundamental scour mechanisms that act upon them, and analyzes the principal failure modes that emerge from sustained or episodic erosion processes. A structured summary of these failure modes and their governing conditions is presented in Table 2, which provides an integrated framework for understanding how hydraulic and geotechnical factors jointly influence roadbed stability.

Table 2. Typical Failure Modes of Highway Roadbeds Near River Bends and Their Governing Conditions.

Failure Mode	Triggering Factors	Sensitive Parameters	Engineering Manifestation
Slope instability	Toe erosion, local scour, flood drawdown	Soil cohesion, slope angle, groundwater pressure	Rotational slips, shallow slides, mass wasting
Foundation weakening	Global scour, channel degradation, piping	Bearing capacity, subgrade stiffness	Settlement, subsidence, loss of embankment support
Pavement deformation	Subgrade loss, differential erosion	Compaction quality, subbase thickness	Cracking, longitudinal depressions, uneven surface
Bank retreat	Repeated toe undercutting, channel migration	Soil erodibility, bend radius, flow velocity	Lateral loss of bank material, roadway encroachment
Internal erosion/piping	High hydraulic gradients, seepage concentration	Permeability, grain-size distribution	Formation of voids, sudden collapses, sinkholes

3.1. Types of Roadbeds Adjacent to Rivers

River-adjacent highways are typically constructed using one of three roadbed configurations, each characterized by distinct structural features and erosion vulnerabilities. The most common type is the embankment roadbed, in which fill materials are placed above the natural ground surface to elevate the roadway. These embankments often extend toward the riverbank and are therefore directly exposed to toe erosion, flow undercutting, and the destabilizing influence of groundwater seepage. Their performance depends heavily on fill material quality, compaction degree, and the integrity of protective revetments or drainage systems [14].

A second category comprises cut-and-fill sections, which combine excavation on the landward side with fill placement toward the riverside. While these configurations provide geometric flexibility in mountainous or narrow river valleys, they introduce sharp lateral transitions in soil stiffness and hydraulic conductivity. Such contrasts make cut-and-fill sections prone to differential settlement, localized erosion, and seepage-driven instabilities, particularly when the river channel lies close to the filled portion.

The third category includes reinforced subgrades, where geosynthetics, retaining structures, or mechanically stabilized earth (MSE) systems are incorporated into the roadbed. These reinforcements enhance overall stability and deformation resistance; however, their effectiveness depends on proper anchorage and protection against scour at the toe. If scouring undermines reinforcement layers or exposes geosynthetic elements, structural integrity may degrade rapidly.

Each roadbed type responds differently to hydraulic loading, but all share common susceptibility to failure when subjected to severe or prolonged scour conditions, especially at curved river sections where hydrodynamic forces concentrate.

3.2. Fundamental Scour Mechanisms

Scour mechanisms acting on river-adjacent roadbeds can be broadly classified into global scour, local scour, toe erosion, and bank retreat, each governed by distinct hydraulic and sedimentary processes.

Global scour refers to the overall lowering of the riverbed across a wide channel cross-section, often occurring during large floods or long-term channel degradation.

Global scour reduces vertical support beneath the bankline and roadbed, lowering the threshold for slope instability and exposing deeper soil layers to erosive forces.

Local scour, by contrast, develops in confined zones where hydraulic energy becomes concentrated. At curved river sections, local scour typically occurs near the outer-bank toe where high-velocity flow and secondary currents converge. Local scour pits can grow rapidly during peak flows and may laterally undermine the base of roadbed slopes.

Toe erosion is one of the most critical mechanisms for embankment stability. As the foot of the slope is gradually eroded, the upper slope loses foundational support, triggering progressive mass wasting, block failures, or rotational slips. Toe erosion is often exacerbated by turbulence structures such as horseshoe vortices and by high-frequency flow fluctuations during storm events.

Bank retreat results from repeated cycles of toe undercutting, slope collapse, and subsequent lateral migration of the river channel toward the roadbed. Over time, bank retreat can remove substantial portions of embankment material and can lead to chronic instability even during moderate flows.

These processes are closely linked to granular-scale mechanisms. Soil detachment occurs when applied shear stresses exceed the cohesive or frictional resistance of the bank material. Granular transport mobilizes detached particles downstream, continually exposing fresh soil to erosion. Piping, a seepage-induced phenomenon, develops when hydraulic gradients drive subsurface flow through the roadbed or bank, removing fine particles and creating internal voids. Piping can drastically weaken the structural framework of the subgrade and often precedes sudden slope failures.

Together, these mechanisms form a coupled hydraulic–geotechnical system in which river flow, sediment transport, and soil behavior interact continuously, especially under the intensified forces present at river bends.

3.3. Failure Modes Under Scour Conditions

Failure modes in river-adjacent highway roadbeds arise from the combination of hydraulic attack and geotechnical degradation. One of the most common outcomes is slope instability, triggered when toe erosion or piping reduces the resisting forces along a potential failure surface. Instability may manifest as shallow slides, rotational failures, or deep-seated mass movements, depending on soil properties and slope geometry. The progression of such failures is often accelerated during flood drawdown conditions when rapid declines in water level induce transient pore pressure imbalances.

Foundation weakening represents another major failure mode. As scour removes supporting soil beneath embankment toes or reinforced subgrades, bearing capacity decreases, leading to uneven settlement or subsidence. In severe cases, partial collapse of the embankment can occur, compromising the integrity of the roadway structure above.

A further consequence is pavement deformation, which includes longitudinal cracking, differential settlement, and surface undulations. Pavement damage arises from progressive loss of support in the subgrade and subbase layers as scour undermines the lower portions of the embankment. These deformations often serve as early indicators of deeper structural problems.

The overall behavior is governed by erosion–deformation coupling, in which hydraulic erosion weakens the soil structure, promoting deformation, while resulting deformation exposes new surfaces to further erosion. This positive feedback loop is particularly pronounced in soft soils or loose, non-cohesive sediments that are highly susceptible to detachment and transport.

4. Influencing Factors of Roadbed Scour at Curved Sections

Roadbed scour at curved river sections is controlled by a complex interplay of hydraulic, geometric, geotechnical, and anthropogenic factors. Unlike straight river reaches, curved segments exhibit highly heterogeneous flow fields and spatially uneven sediment transport capacity, making nearby highway embankments and subgrades more vulnerable to erosion. Understanding these influencing factors is crucial for establishing accurate risk assessments and designing targeted protection measures. This chapter synthesizes the key variables that govern scour intensity and patterns at such locations.

4.1. Hydraulic Factors

Hydraulic conditions are the primary drivers of roadbed scour, particularly during high-flow events when the river's capacity to entrain and transport sediment increases sharply. In curved channels, the flow pattern is dominated by secondary currents, which generate high shear stress zones along the outer bank. These zones amplify sediment detachment and create deeper scour holes near the roadbed toe. During floods, the Froude number often rises, indicating a transition towards supercritical flow behavior; under such conditions, both turbulence intensity and boundary shear stress escalate, accelerating erosion processes.

Another critical hydraulic influence is water level fluctuation, especially rapid rises during storm events or upstream reservoir releases. Sudden increases in stage level alter the pressure gradient across the embankment and can destabilize the near-slope soil structure. Similarly, rapid drawdown after peak flow may induce negative pore-pressure gradients, weakening the embankment and enhancing bank collapse. Extreme hydrological events, including once-in-decades floods and prolonged high-flow episodes, contribute disproportionately to roadbed scour by sustaining elevated shear forces over extended periods. Therefore, hydraulic variability—rather than mean annual discharge—often governs the severity of scour at curved sections.

4.2. Geometrical and Alignment Factors

The geomorphic configuration of the river bend plays a decisive role in determining local scour patterns. The bend curvature ratio (defined as river bend radius relative to channel width) strongly influences lateral flow acceleration. Sharper bends generate stronger outward-directed centrifugal forces, intensifying erosion at the outer bank where highways are often constructed due to topographic constraints. Variations in river width further modulate flow concentration; constricted sections force higher velocities, magnifying shear stress acting on the bank.

The horizontal alignment of the roadbed relative to the riverbank is another critical factor. When the toe of the embankment is located close to the active channel, even minor bank retreat can expose the subgrade to direct flow attack. Insufficient buffer distance reduces the natural energy dissipation provided by riparian vegetation and bank materials. In addition, river planform migration over multi-year cycles may progressively shift high-velocity zones toward the roadbed, transforming once-safe segments into high-risk sites. Thus, highway alignment decisions must consider both current and potential future river geometries.

4.3. Geotechnical Factors

The resistance of the roadbed and bank materials to erosive forces depends largely on their geotechnical properties. Soil erodibility, influenced by particle size distribution, plasticity, and mineral composition, determines the ease with which sediment can be detached. Cohesive soils—such as clay-rich materials—may initially resist erosion but can fail rapidly once protective bonds break down under prolonged shear stress. In contrast, non-cohesive sandy materials are highly susceptible to scour due to limited interparticle bonding.

Gradation and compaction quality significantly influence the structural integrity of roadbed fill. Poorly graded materials or insufficient compaction create preferential flow paths, allowing seepage to undermine internal stability. Groundwater seepage is especially critical; upward seepage pressures can weaken the embankment toe and initiate piping or sloughing failures. Conversely, properly designed drainage systems, such as toe drains and filter layers, help dissipate pore water pressures and reduce internal erosion. Geotechnical deterioration caused by repeated wetting–drying cycles, freeze–thaw processes, or seasonal groundwater changes can further reduce soil strength and increase susceptibility to scour.

4.4. Human Activities and Environmental Change

Human interventions often modify natural river dynamics, directly influencing scour processes near roadways. River engineering works, including channel straightening, bank revetments, and spur dikes, alter flow distribution and may unintentionally shift high-velocity zones toward the outer bank. Sand mining, especially when conducted near the toe of a river bend, creates artificial deep pools that accelerate local flow velocities and destabilize adjacent roadbeds. Similarly, vegetation removal along the riverbank decreases root reinforcement and reduces hydraulic roughness, making the bank more prone to erosion.

Environmental changes further exacerbate scour risks. Climate change has intensified the frequency and magnitude of extreme rainfall and flood events in many regions. Higher peak discharges and shortened flood recurrence intervals lead to more sustained high-velocity flows impacting the roadbed. In addition, altered sediment supply due to upstream regulation or watershed land-use changes can modify riverbed morphology and increase channel instability. These combined influences highlight the need for adaptive management strategies that consider long-term environmental trends rather than relying solely on historical hydrological records.

5. Protection, Monitoring, and Modeling Approaches

Effective management of roadbed scour at curved river sections requires a combination of engineering protection, real-time monitoring, and robust numerical or physical modeling. Because curved reaches concentrate hydraulic forces toward the outer bank and induce complex sediment dynamics, conventional countermeasures designed for straight channels are often insufficient. This chapter reviews the most widely adopted protection strategies, emerging monitoring technologies, and modeling approaches that have shown promise for improving prediction accuracy and reducing long-term risk.

5.1. Engineering Protection Measures

Engineering countermeasures remain the first line of defense against roadbed scour. The most common approach involves reinforcing the embankment toe through armoring techniques, which directly resist erosive shear forces. Riprap is widely used due to its adaptability and ability to dissipate hydraulic energy through interstitial flow. Properly graded layers of rock, when placed with sufficient thickness, offer durable protection for moderate to high flow velocities. Gabions, consisting of wire mesh baskets filled with rock, provide additional flexibility on uneven foundations and can better accommodate minor settlement without losing structural integrity. These systems are especially effective along outer river bends where direct flow impact is concentrated.

Beyond toe protection, revetment systems serve to stabilize the entire slope surface. Hard revetments such as concrete slabs, block mats, or grouted riprap offer strong resistance to erosion but can disrupt natural bank processes and promote scouring at their edges. Retaining structures, including sheet piles and reinforced earth walls, are used when space constraints prevent gentle slopes or when the roadbed lies extremely close to the channel. In recent years, geosynthetics—geotextiles, geogrids, and geocells—have been integrated into revetment systems to improve soil retention, promote vegetation growth, and enhance structural stability while maintaining permeability.

In cases where modifying the river hydraulics is feasible, river training works provide broader, system-oriented protection. Spur dikes (also called groynes) extend from the bank into the channel to deflect flow away from the roadbed and encourage sediment deposition near the outer bend. Guide banks are used to streamline flow paths, especially near bridge approaches, but can also be applied along highway embankments to reduce local turbulence. Properly designed river training structures can significantly reduce scour intensity; however, they must be tailored to the bend geometry to avoid unintended downstream impacts.

5.2. Monitoring Techniques

Traditional field inspections are insufficient for detecting early-stage scour, particularly in dynamically evolving curved channels. Modern remote sensing and in-situ monitoring technologies provide more comprehensive spatial and temporal coverage.

UAV photogrammetry has become a valuable tool for rapid, high-resolution monitoring of riverbank retreat, channel migration, and embankment deformation. The ability to repeatedly capture orthophotos and digital surface models enables precise quantification of morphological changes over time. Similarly, LiDAR scanning—whether airborne or terrestrial—provides detailed three-dimensional point clouds that reveal subtle scour features, undercut slopes, and surface roughness variations. Satellite-based remote sensing offers coarse-resolution but long-term data that are useful for identifying large-scale channel shifts influenced by seasonal hydrology and extreme events.

To directly track deformation and scour progression near the roadbed, in-situ sensors are increasingly employed. Buried scour sensors can detect changes in embedment depth and provide real-time warnings when sediment is removed at the toe. Pore-pressure transducers help evaluate internal erosion risks associated with groundwater seepage. For surface displacement monitoring, GNSS deformation stations and total-station-based prism tracking offer millimeter-level accuracy, allowing early detection of embankment settlement or lateral movement. Integrating these sensing technologies through wireless telemetry enables continuous condition assessment and supports predictive maintenance strategies.

5.3. Numerical and Physical Modeling

Given the complex flow structures generated at curved river sections, numerical modeling is essential for predicting scour evolution and evaluating protection measures. Two-dimensional (2D) hydrodynamic models are widely used for simulating depth-averaged flow patterns and shear stress distribution. Although suitable for large-scale assessments, 2D models may oversimplify secondary flow structures critical to outer-bank scour. Three-dimensional (3D) models based on Reynolds-Averaged Navier–Stokes (RANS) equations offer improved resolution of turbulence and near-bed velocity gradients, making them more accurate for simulating localized scour holes. For detailed analysis of flow–structure interactions, Large Eddy Simulation (LES) provides even higher fidelity by resolving large-scale turbulent eddies, though at significantly greater computational cost.

Emerging approaches focus on coupled flow–sediment–structure simulations, which integrate hydraulic forces, sediment transport, and structural deformation. These models allow dynamic prediction of scour progression under varying hydrological conditions and help evaluate the long-term performance of protection systems. However, their accuracy depends on high-quality input data and rigorous calibration.

Despite advances in numerical modeling, flume-based physical experiments remain indispensable. Laboratory models enable direct observation of flow patterns, vortex development, and sediment transport under controlled conditions. They also facilitate testing of multiple countermeasure configurations before field deployment. Hybrid approaches that combine physical and numerical modeling are increasingly adopted to improve reliability and reduce uncertainty.

To synthesize the key engineering, monitoring, and modeling measures discussed in this chapter, Table 3 provides a consolidated summary of common approaches, their suitable application conditions, and their practical advantages and limitations.

Table 3. Summary of Protective and Monitoring Measures for Scour Control.

Measure Type	Applicable Conditions	Advantages	Limitations
Riprap / Gabion Toe Armoring	Outer-bank high-velocity zones; moderate to severe scour	Simple installation; high durability	May require large rock; prone to undermining without filter layers
Revetments / Retaining Structures	Steep slopes; limited space; close proximity to roadbed	Strong erosion resistance; structural stability	Hard surfaces alter natural processes; higher cost
Geosynthetic Reinforcement	Erodible soils; need for lightweight solutions	Enhances soil retention; promotes vegetation	Susceptible to UV degradation if exposed
Spur Dikes / Guide Banks	Curved reaches requiring flow redirection	Reduces direct attack on bank; promotes sediment deposition	Requires careful hydraulic design; potential downstream effects
UAV / LiDAR Monitoring	Rapid assessment of channel geometry	High spatial resolution; repeatable surveys	Dependent on weather; requires data processing expertise
In-situ Scour & GNSS Sensors	Real-time detection of toe erosion and deformation	Early warning capability; continuous monitoring	Installation cost; sensor burial challenges

6. Conclusions and Future Perspectives

Highway roadbeds constructed along curved river sections are inherently vulnerable to scour due to the concentration of hydraulic forces, complex secondary flows, and dynamic sediment transport processes. This review synthesized current understanding of the hydrodynamic characteristics at river bends, the mechanisms of roadbed–river interaction, and the various failure modes that arise when erosion progresses unchecked. Across the literature, a consistent conclusion emerges: scour at curved river-adjacent highway sections is not governed by a single factor but results from the interaction of flow hydraulics, bend geometry, soil erodibility, and external disturbances, including human activities and climate-driven hydrological changes.

The review further examined existing engineering protection methods, monitoring technologies, and modeling approaches. While conventional toe armoring, revetments, and river training structures remain central to engineering design, new tools such as UAV photogrammetry, LiDAR scanning, in-situ scour sensors, and advanced numerical modeling frameworks are transforming modern scour assessment and mitigation practices. Still, the complexity of curved channel hydraulics poses persistent challenges, particularly under extreme events that exceed design assumptions.

Looking ahead, several research directions hold promise for improving the resilience and sustainability of river-adjacent highway systems. First, AI-driven scour prediction models—especially those utilizing machine learning and hybrid physical–data approaches—can enhance early-warning capabilities by detecting emerging scour patterns from large-scale monitoring datasets. Second, fully coupled hydro–geotechnical–

structural modeling is essential for capturing the dynamic feedback between flow forces, sediment transport, and roadbed deformation. Advancements in 3D computational fluid dynamics, sediment dynamics algorithms, and soil-structure interaction modeling will support this integration. Third, climate-resilient design frameworks are urgently needed, considering projected increases in extreme floods, rapid water-level fluctuations, and long-term channel migration driven by climate change. Incorporating scenario-based hydrological inputs into design codes will be critical. Finally, ecological and sustainable bank protection solutions, such as bioengineering techniques, vegetative revetments, and nature-based hydraulic modifications, can provide effective scour resistance while preserving riverine ecosystems.

In conclusion, mitigating scour hazards in curved river-adjacent highway sections requires interdisciplinary approaches that bridge hydraulics, geotechnical engineering, geomorphology, and intelligent monitoring. Continued innovation in modeling, sensing, and sustainable design will be key to ensuring safer and more resilient transportation infrastructure in dynamic river environments.

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